FECM/NETL CO_2 Transport Cost Model (2022): Model Overview

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Authors and Acknowledgements

David Morgan[1]: Conceptualization, Methodology, Software, Validation, Investigation, Writing – Original Draft, Writing – Review & Editing; **Allison Guinan**,[1,2]: Methodology, Validation, Formal Analysis, Writing – Original Draft, Writing – Review & Editing, Visualization, Supervision; **Alana Sheriff**[1,2]: Methodology, Software, Validation, Investigation, Writing – Original Draft, Writing – Review & Editing

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[1] National Energy Technology Laboratory (NETL)
[2] NETL support contractor

Presentation Outline

- FECM/NETL CO_2 Transport Cost Model (CO2_T_COM) overview
- Fundamental modules
- CO2_T_COM sheets (or worksheets)
- How CO2_T_COM works
- Example model results
- Acronyms and abbreviations
- References

FECM/NETL CO_2 Transport Cost Model (CO2_T_COM) Overview

Purpose: Mimic CO_2 transport operations to estimate costs associated with potential pipeline project

- Excel-based tool that estimates revenues and capital, operating, and financing costs of transporting CO_2 by pipeline[1]
  - Assumes CO_2 is present in pipeline in dense (i.e., liquid) phase
  - Single point-to-point pipeline
  - Booster pumps may be included along pipeline
- Includes two fundamental modules: financial and engineering
- Consists of 12 worksheets (or sheets) along with VBA macros and user-defined functions
- Has custom ribbon tab (“CO2_T_COM”) that provides ability to run different options of “Goal_Seek_Price” VBA macro to generate variety of outputs
- Allows user to adjust values for input variables (e.g., CO_2 mass flow rate, pipeline length, project duration, financial inputs) to fit requirements of their project
- Has ability to calculate costs in real (i.e., constant) or nominal (i.e., escalated) dollars

Fundamental Modules

Financial ("Main" sheet)

- Primary interface for model which allows user to enter key inputs and provides key results
- Houses financial model that includes methodology to calculate costs in real or escalated dollars
- Includes cash flows of revenues, capital costs, operating expenses, depreciation, taxes, and earnings
- Provides annual escalation factors for calculating nominal value of cash flows and annual discount factors for calculating present value of cash flows
- Calculates NPV of project using WACC methodology
- See Section 2 in model's user's manual for more information on this module[2]

Fundamental Modules

Financial ("Main" sheet): Summary of key inputs and outputs

Key Technical and Operational Inputs

- Pipeline length
- Number of booster pumps (used to divide pipeline into equal length segments)
- Pressure at beginning and end of pipeline, same as pressure at beginning and end of pipe segment
- Net elevation change across entire pipeline
- Average annual CO_2 mass flow rate and capacity factor (used to calculate maximum CO_2 mass flow rate)
- Duration of construction period and duration of operating period

Key Financial Variables

- Fraction equity (remainder is debt)
- Minimum desired internal rate of return on equity
- Interest rate on debt
- Effective tax rate (federal income tax and state and local taxes)
- Escalation rate from base year of 2011 to first year of project
- Escalation rate from first year of project to later years

Key Outputs

- Minimum inner diameter of pipe given maximum CO_2 mass flow rate, pipeline length, and number of booster pumps
- Nominal or standard pipeline diameter
- NPV for project
- Internal rate of return for project

Fundamental Modules

Financial (“Main” sheet): Detailed description of operational key inputs

Parameter	Default Value	Location in “Main” Sheet	Note
First-year price to transport CO_2 (2011$/tonne))	---	Cell E10	User input is only applied when running model in basic mode with no macro use (Section 1.2.1 in model’s user’s manual[2])
Average annual mass flow of CO_2 transported (Mtonnes/yr)	4.30	Cell E11	Default value per “Carbon Dioxide Transport and Storage Costs in NETL Studies” QGESS[3]
Capacity factor (%)	85	Cell E12	Default value per “Carbon Dioxide Transport and Storage Costs in NETL Studies” QGESS[3]; capacity factor used to calculate maximum CO_2 mass flow rate
Length of pipeline (mi)	62	Cell E14	Default value per “Carbon Dioxide Transport and Storage Costs in NETL Studies” QGESS[3]
Number of booster pumps	1	Cell E15	Only use when it is desired to use user-defined booster pumps instead of optimal when running any macro option; toggle “Optimal Pump Number” off in “CO2_T_COM” ribbon tab
Change in elevation from inlet to outlet of pipeline (ft)	0	Cell E16	If outlet is at higher elevation than inlet, change is positive
Calendar year for start of project (yr)	2018	Cell E60	
Duration of construction (yr)	3	Cell E61	Can be up to five years
Duration of operation (yr)	30	Cell E62	Must be less than 95 years Default value per “Carbon Dioxide Transport and Storage Costs in NETL Studies” QGESS[3]
Inlet pressure for pipeline (psig)	2,200	Cell E76	Default value per “Carbon Dioxide Transport and Storage Costs in NETL Studies” QGESS[3]
Outlet pressure for pipeline (psig)	1,200	Cell E78	Default value per “Carbon Dioxide Transport and Storage Costs in NETL Studies” QGESS[3]
Equation to use for calculating capital costs for pipeline (specify one)	Parker	Cell E82	PARKER for equations from Parker[4] MCCOY for equations from McCoy and Rubin[5] RUI for equations from Rui et al.[6]
Region of United States or Canada (specify one)	MW	Cell E83	NE (northeast United States), SE (southeast United States), MW (midwest United States), Cen (central United States), SW (southwest United States), West (western United States), Can (Canada) Note: Equations of Parker have no regional component, and equations of McCoy and Rubin do not have costs for Canada

Key inputs are described in Section 2.2 of model’s user’s manual[2]

Fundamental Modules

Financial ("Main" sheet): Detailed description of financial key inputs

Parameter	Default Value	Location in "Main" Sheet	Note
Percent equity (%)	45	Cell E45	Remainder is debt Per "Cost Estimation Methodology for NETL Assessments of Power Plant Performance" QGESS[7]
Cost of equity or minimum internal rate of return on equity (%/yr)	10.77 (real) 13.00 (nominal)	Cell E46	See Appendix A in model's user's manual[2]
Cost of debt or interest rate on debt (%/yr)	3.91 (real) 6.00 (nominal)	Cell E47	See Appendix A in model's user's manual[2]
Total effective tax rate (%/yr)	25.74	Cell E48	21% federal corporate income tax and 6% state and local taxes with effective tax rate reflecting deduction of state and local taxes from federal income taxes See Appendix A in model's user's manual[2]
Escalation rate from base year to project start year (%/yr)	2.2	Cell E49	See Appendix A in model's user's manual[2]
Escalation rate beyond project start year (%/yr)	0 (real) 2.3 (nominal)	Cell E51	See Appendix A in model's user's manual[2]
Project contingency factor (%)	15	Cell E52	Applied to all capital costs (project contingency in range of 15–30% is recommended for level of detail provided by cost equations used in model since miscellaneous cost category in pipeline capital costs includes contingency [and some taxes])[7]
Depreciation method – recovery period for depreciation	DB150 – 15 years	Cell E53	DB150 – 15 years, SL – 15 years, or SL – 22 years

Fundamental Modules

Engineering ("Eng Mod" sheet): Comprised of three parts

- Part 1: Engineering calculations
  - Contains technical calculations and some areas for user input
  - Based on user specified number of pumps, model divides pipeline into equal length segments with pump at end of each segment except last one
  - Based on segment length, user specified pressure drop across segment, maximum CO_2 mass flow rate, and elevation change across segment:
    - Model calculates smallest inner pipe diameter that can sustain maximum CO_2 flow rate with pressure drop and elevation change
    - Model determines smallest standard or nominal pipe size (i.e., diameter) with inner pipe diameter equal to or greater than this smallest inner pipe diameter
      - Nominal pipe sizes available in model: 4, 6, 8, 10, 12, 16, 20, 24, 30, 36, 42 and 48 in
      - Pipe sizes less than or equal to 12 in are inner diameters; pipe sizes greater than 12 in are outer diameters
    - **Note**: If maximum CO_2 mass flow rate is too large and pipe segment too long, then smallest inner pipe diameter may exceed inner diameter for 48-in pipe
      - In this case, model specifies nominal pipe size of 2,000 in
      - This outcome indicates user must increase number of booster pumps to decrease pipe segment length so that nominal pipe size of 48 in or less is viable
  - Based on maximum CO_2 mass flow rate and pressure increase across pump, model calculates maximum power required to operate pump

Fundamental Modules

Engineering (“Eng Mod” sheet): Comprised of three parts (cont’d)

- Part 2: CAPEX (capital costs or expenses)
  - Model calculates
    - Capital costs for pipeline
      - User specifies one of three regression equations for calculating capital costs based on pipeline length and nominal pipe size
      - Capital cost regression equations are for natural gas pipelines and have four components: 1) materials, 2) labor, 3) right of way and damages, and 4) miscellaneous
      - Natural gas pipelines typically operate at lower pressures than CO_2 pipelines, so CO_2 pipelines generally need thicker pipe walls
        - Model calculates factor based on nominal pipe size that is used to increase natural gas pipeline capital costs to make costs reflective of CO_2 pipeline capital costs
    - Capital costs for booster pumps based on maximum power requirement for pump
    - Capital costs for control system and surge tank
- Part 3: OPEX (operating costs or expenses)
  - Model calculates annual O&M costs for each equipment type
  - Annual cost of electricity needed to operate pumps is based on maximum pump power rating, capacity factor for pipeline, and user specified price of electricity

See Section 3 in model’s user’s manual for more information on this module[2]

Fundamental Modules

Engineering ("Eng Mod" sheet): Detailed description of key inputs

Parameter	Default Value	Location in "Eng Mod" Sheet	Note
Temperature of ground where pipes are buried (°F)	53	Cell D7	
Pump efficiency (%)	75	Cell D17	From McCollum and Ogden[8]
Method for calculating minimum pipe diameter (specify one)	1	Cell D41	1 = methodology for incompressible fluid (i.e., liquid) using equations presented in Appendix B in model's user's manual[2] 2 = methodology for compressible fluid (i.e., gas) using equations presented in Appendix B in model's user's manual[2]
Method for calculating Fanning friction factor (specify one)	3	Cell D42	1 for equation developed by Haaland 2 for equation developed by Zigrang and Sylvester 3 for Colebrook-White equation See Appendix B in model's user's manual[2]
CO_2 surge tank capital costs ($)	701,600	Cell D126	In 2000$ Per supplementary spreadsheet to "Estimating Carbon Dioxide Transport and Storage Costs" QGESS[9]
Pipeline control system capital costs ($)	94,000	Cell D127	In 2000$ Per supplementary spreadsheet to "Estimating Carbon Dioxide Transport and Storage Costs" QGESS[9]

Key inputs are described in Section 3.4 of model's user's manual[2]

Fundamental Modules

Engineering ("Eng Mod" sheet): Detailed description of key inputs (cont'd)

Parameter	Default Value	Location in "Eng Mod" Sheet	Note
Pump costs – fixed capital costs ($)	70,000	Cell D133	In 2005$ Per McCollum and Ogden[8]
Pump costs – variable capital costs ($/kW)	1,110	Cell D134	In 2005$/kW Per McCollum and Ogden[8]
Method for calculating annual pipeline O&M costs (specify one)	2	Cell D144	1 = use fixed O&M costs per mile of pipeline independent of diameter 2 = use fraction of capital costs, which depend on pipeline length and diameter
Annual pipeline O&M costs per mile of pipe ($/mi-yr)	5,000	Cell D146	In 1999$/mi-yr Per supplementary spreadsheet to "Estimating Carbon Dioxide Transport and Storage Costs" QGESS[9]
Percent of CAPEX to use as annual O&M costs for pipeline (%)	2.5	Cell G150	Per McCollum and Ogden[8]
Percent of pump, control system, and surge tank capital costs to use as annual O&M costs for these pieces of equipment (%)	4.0	Cell G157	Best professional judgment
Electricity for pumping ($/MW-hr)	68.20	Cell D162	In 2011$/MW-hr From EIA, electricity price for industrial sector[10]

CO2_T_COM Sheets (or Worksheets)

- Critical to model's performance
  - "Main" sheet: Core interface, houses financial module, and provides key inputs for project along with main results and findings
  - "Combo Results" sheet: Provides way to simultaneously run multiple scenarios and shows key results for each scenario
  - "Eng Mod" sheet: Engineering module, which includes equations for calculating engineering variables, and capital costs and operating expenses for pipeline equipment
- Associated with "Process_Cases" VBA macro
  - "Cases" sheet: Includes inputs for running macro, button for running macro, and macro-generated outputs/results
    - User defines different cases where each case has following inputs: Pipeline length, maximum CO_2 mass flow rate, capacity factor (or average annual CO_2 mass flow rate), and elevation change along pipeline
    - User specifies up to 100 results that should be generated for each case
    - Macro processes each case and generates user-requested results
  - "Cases_def" sheet: Provides brief description of input variables and results generated by macro
    - If user specifies results that are not in original version of "Cases" sheet, user can add descriptions of these results to this sheet

CO2_T_COM Sheets (or Worksheets) (cont'd)

- Provide useful information but not critical to model's operation
  - "READ_ME_FIRST" sheet: Provides brief overview of model and information on color and font conventions, along with fundamental model assumptions
  - "PL Pressure Relation" sheet: Includes data for developing factor to translate natural gas pipeline capital costs to CO_2 pipeline capital costs
  - "Cost Indices" sheet: Contains variety of cost indices used to adjust costs to base year of 2011
  - "Pipe Cap" sheet: Has tables with capital costs for different aspects of constructing natural gas pipeline using three different cost equations
  - "Pipe Cap plot" sheet: Includes tables and plots of capital costs for different aspects of constructing natural gas pipeline using three different cost equations
    - Plots are used in user's manual[2]
- Hidden and used internally by model or developers; thus, should not be modified by user
  - "Parameters" sheet: Contains logic behind drop-down menus and items in "Main" and "Eng Mod" sheets and "CO2_T_COM" ribbon tab
  - "Version" sheet: Includes information used by developers to track edits made within model

How CO2_T_COM Works

Overview

- CO2_T_COM has several operating modes
  - All except one involve running "Goal_Seek_Price" VBA macro from CO2_T_COM ribbon tab
- Critical inputs for modes involve following variables on "Main" sheet
  - First-year price to transport CO_2 (may be calculated by "Goal_Seek_Price" macro depending on mode)
  - Number of booster pumps (may be calculated by "Goal_Seek_Price" macro depending on mode)
  - Length of pipeline
  - Annual average CO_2 mass flow rate and capacity factor for pipeline
  - Elevation change along pipeline
- Critical inputs can be specified by user
  - Two inputs, first-year CO_2 price and number of booster pumps, will be calculated by macro depending on mode
  - Other modes provide outputs as function of number of booster pumps, length of pipeline, annual average CO_2 mass flow rate, and/or elevation change along pipeline to show sensitivity of outputs to changes in these input variables

How CO2_T_COM Works

Basic Mode with No Macro Use

- In this mode, user specifies all inputs identified on Slide 16 plus all others on slides 8, 9, 12, and 13
- Model calculates following key outputs:
  - Minimum inner diameter of pipe and nominal pipe size
  - NPV for project
  - Internal rate of return for project
- See Section 1.2.1 in model's user's manual for more information on this mode[2]

How CO2_T_COM Works

Basic Mode with No Macro Use (cont'd)

Note: This mode gives user greatest control over values for input variables

- User can change first-year CO_2 price, and this will change NPV for project
- If NPV for project is greater than zero
  - First-year CO_2 price brings in enough revenue to cover capital costs, O&M costs, taxes, and principal and interest on debt, while providing return on equity that exceeds minimum desired internal rate of return on equity
  - Internal rate of return for project exceeds WACC
- If NPV for project equals zero
  - First-year CO_2 price brings in enough revenue to cover capital costs, O&M costs, taxes, and principal and interest on debt, while just barely providing return on equity that equals minimum desired internal rate of return on equity
- First-year CO_2 price that results in NPV for project equal to zero is very useful metric
  - This is lowest price pipeline operator can charge for transporting CO_2 and still have viable project
  - This is called **first-year break-even CO_2 price**

How CO2_T_COM Works

Basic Mode Using Macro to Calculate First-Year Break-Even Price of CO_2

- Because **first-year break-even CO_2 price** is important metric, CO2_T_COM provides this mode which runs "Goal_Seek_Price" macro to calculate this CO_2 price
- User specifies inputs from slide 16 and others from slides 8, 9, 12, and 13
  - Entry for first-year CO_2 price is over-written by macro
- In "CO2_T_COM" ribbon tab
  - Toggle "Optimal Pump Number" off (user input)
    - Toggled off for this discussion to use user-desired inputs for number of booster pumps
  - Select "Basic" in "Macro Option" drop-down menu
  - Press "Break-even Analysis" button to run "Goal_Seek_Price" macro
- After macro is complete
  - Text box appears with message: "Execution Complete for "Goal_Seek_Price Macro! Run time of X minutes"

How CO2_T_COM Works

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Basic Mode Using Macro to Calculate First-Year Break-Even Price of CO_2 (cont'd)

- Key outputs after "Goal_Seek_Price" macro has executed
  - Macro has over-written user input for first-year CO_2 price on "Main" sheet with **first-year break-even CO_2 price** (rounded up to nearest penny)
  - NPV for project on "Main" sheet is slightly above zero
    - NPV for project exceeds zero because first-year break-even CO_2 price is rounded up
  - Internal rate of return for project on "Main" sheet equals or just exceeds WACC
    - Internal rate of return for project exceeds WACC because first-year break-even CO_2 price is rounded up
- See Section 1.2.2 in model's user's manual for more information on this mode[2]

How CO2_T_COM Works

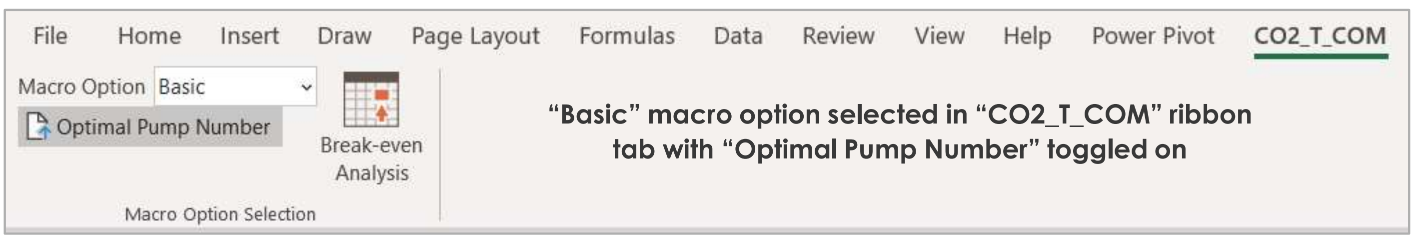
Basic Mode Using Macro to Calculate First-Year Break-Even Price of CO_2 (cont'd)

- This mode allows user to examine influence of number of booster pumps on first-year break-even CO_2 price
  - User can begin with lowest number of booster pumps that is viable (typically zero) and use "Goal_Seek_Price" macro to calculate first-year break-even CO_2 price (current overall lowest first-year break-even CO_2 price); model also reports minimum inner pipe diameter and nominal pipe size
  - If user systematically increases number of booster pumps, pipe segments get shorter and, eventually, minimum inner pipe diameter is reduced enough that smaller nominal pipe size can be used
    - This will reduce capital and O&M cost for pipeline, but increase capital and O&M costs for pumps
    - First-year break-even CO_2 price for this number of booster pumps and associated nominal pipe size may or may not be lower than current overall lowest first-year break-even CO_2 price
  - To find number of booster pumps and associated nominal pipe size that gives overall lowest first-year break-even CO_2 price, user must systematically increase number of booster pumps and record number of booster pumps and nominal pipe size that gives current overall lowest first-year break-even CO_2 price
  - User must continue this process until nominal pipe size is 4 in (smallest nominal pipe size in model) or first year break-even CO_2 price increases to levels many times current overall lowest first-year break-even CO_2 price
- To implement this process manually would be tedious and error prone
  - CO2_T_COM provides mode where macro determines number of booster pumps and associated nominal pipe size that gives overall lowest first-year break-even CO_2 price (see next slide)

How CO2_T_COM Works

Basic Mode Using Macro to Determine Optimal Number of Booster Pumps

- This mode runs "Goal_Seek_Price" macro to determine number of booster pumps and associated nominal pipe size that provides overall lowest first-year break-even CO_2 price
- User specifies inputs from Slide 16 and others from slides 8, 9, 12, and 13
  - Entries for first-year CO_2 price and number of pumps are over-written by macro
- In "CO2_T_COM" ribbon tab
  - Toggle "Optimal Pump Number" on
  - Select "Basic" in "Macro Option" drop-down menu
  - Press "Break-even Analysis" button to run "Goal_Seek_Price" macro
- After macro is complete
  - Text box appears with message: "Execution Complete for "Goal_Seek_Price Macro! Run time of X minutes"



"Basic" macro option selected in "CO2_T_COM" ribbon tab with "Optimal Pump Number" toggled on

How CO2_T_COM Works

Basic Mode Using Macro to Determine Optimal Number of Booster Pumps (cont'd)

- Key outputs after "Goal_Seek_Price" macro has executed
  - Macro has over-written user input for first-year CO_2 price on "Main" sheet with **first-year break-even CO_2 price** (rounded up to nearest penny)
  - Macro has over-written user input for number of booster pumps on "Main" sheet with number of booster pumps that gives lowest overall first-year break-even CO_2 price
    - In cell to right of cell storing number of booster pumps, phrase "Optimal number of pumps" appears
  - NPV for project on "Main" sheet is slightly above zero and Internal rate of return for project on "Main" sheet equals or just exceeds WACC
    - NPV for project exceeds zero and internal rate of return may exceed WACC because first-year break-even CO_2 price is rounded up
- See Section 1.2.3 in model's user's manual for more information on this mode[2]

Note: This mode is likely to be most popular, since it provides information that users are generally most interested in: The combination of number of pumps and nominal pipe size that gives overall lowest first-year break-even CO_2 price

How CO2_T_COM Works

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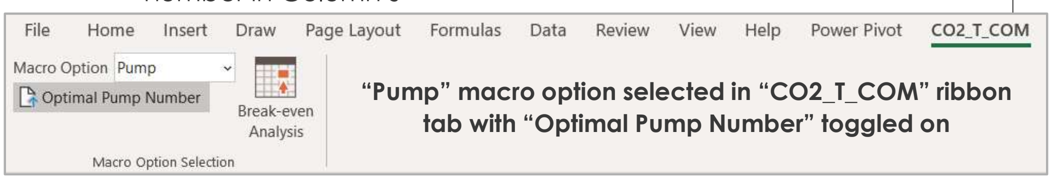
Overview of remaining modes

- Remaining modes run “Goal_Seek_Price” macro to fill in tables 1B, 1C, 1D, or 1E on “Main” sheet
  - These tables show dependence of output variables on specific input variables
  - Output variables provided in each table are
    - Number of booster pumps (except Table 1B where this is input), minimum inner pipe diameter, nominal pipe size, and first-year break-even CO_2 price
- Input variables associated with each table:
  - Table 1B: User inputs different number of booster pumps
  - Table 1C: User inputs different pipeline lengths
  - Table 1D: User inputs different average annual CO_2 mass flow rates
  - Table 1E: User inputs different values of average annual CO_2 mass flow rate, pipeline length, and elevation change along pipeline

How CO2_T_COM Works

Using Macro to Calculate Results for Multiple Values of Input Variables (Table 1B in "Main" sheet provides results for different numbers of booster pumps)

- User specifies inputs from Slide 16 and others from slides 8, 9, 12, and 13
- User enters up to 21 different number of booster pumps for evaluation in Column J in Table 1B on "Main" sheet
- In "CO2_T_COM" ribbon tab
  - Toggle "Optimal Pump Number" on (optimal number of pumps) or off (user input)
  - Select "Pump" in "Macro Option" drop-down menu
  - Press "Break-even Analysis" button to run "Goal_Seek_Price" macro
- After macro is complete
  - Text box appears with message: "Execution Complete for "Goal_Seek_Price Macro! Run time of X minutes"
  - Macro returns first-year break-even CO_2 price, minimum inner pipe diameter, and nominal pipe diameter for each pump number in Column J



"Pump" macro option selected in "CO2_T_COM" ribbon tab with "Optimal Pump Number" toggled on

- After macro is complete (cont'd)
  - Results for number of pumps that give lowest overall first-year break-even CO_2 price provided in last row of Table 1B (if "Optimal Pump Number" toggled on)
- See Section 1.2.4 in model's user's manual for more information on this mode[2]

	J	K	L	M	N	O
7	B. First-Year Break-Even Price of CO2 as a Function of Number of Pumps					
8	Enter a blank cell in column J to indicate the end of input values					
9	Num. of pumps	First Year Price	First Year Price	First Year Price	Minimum Inner	Selected Nominal
10	where results are	base year	first yr of proj	first yr of transp	Pipe Diameter	Pipe Diameter
11	desired	2011$/tonne	2018$/tonne	2021$/tonne	in	in
12	0	2.23	2.60	2.78	13.17	16.00
13	1	1.90	2.21	2.37	11.51	12.00
14	2	2.16	2.52	2.70	10.65	12.00
15	3	2.42	2.82	3.02	10.07	12.00
16	4	2.50	2.91	3.12	9.65	10.00
17	5	2.76	3.21	3.44	9.31	10.00
18	7	3.28	3.82	4.09	8.81	10.00
19	10	4.06	4.73	5.06	8.29	10.00
20	15	5.20	6.06	6.49	7.71	8.00
21	20	6.49	7.56	8.09	7.32	8.00
22	25	7.79	9.07	9.71	7.02	8.00
23	30	9.09	10.59	11.34	6.79	8.00
24	35	10.39	12.10	12.95	6.60	8.00
25	40	11.68	13.60	14.56	6.43	8.00
26	45	12.98	15.12	16.19	6.29	8.00
27	50	14.28	16.63	17.80	6.17	8.00
28	75	20.63	24.02	25.72	5.71	6.00
29	100	27.12	31.58	33.81	5.41	6.00
30	200	53.07	61.80	66.16	4.74	6.00
31						
32						
33	1	1.90	2.21	2.37	11.51	12.00
34	Optimal No. Pumps					

Example inputs and results for Table 1B on "Main" sheet with "Optimal Pump Number" toggled on

How CO2_T_COM Works

Using Macro to Calculate Results for Multiple Values of Input Variables (Table 1C in “Main” sheet provides results for different pipeline lengths)

- User specifies inputs from Slide 16 and others from slides 8, 9, 12, and 13
  - User enters number of booster pumps if fixed number of booster pumps is desired for all outputs in Table 1C
- User enters up to 45 different pipeline lengths for evaluation in Column Q in Table 1C on “Main” sheet
- In “CO2_T_COM” ribbon tab
  - Toggle “Optimal Pump Number” on (optimal number of pumps) or off (user input)
  - Select “Length” in “Macro Option” drop-down menu
  - Press “Break-even Analysis” button to run “Goal_Seek_Price” macro
- After macro is complete
  - Text box appears with message: “Execution Complete for "Goal_Seek_Price Macro! Run time of X minutes”

“Length” macro option selected in “CO2_T_COM” ribbon tab with “Optimal Pump Number” toggled off

- After macro is complete (cont’d)
  - Macro returns first-year break-even CO_2 price, number of pumps, minimum inner pipe diameter, and nominal pipe diameter for each pipeline length in Column Q
- See Section 1.2.4 in model’s user’s manual for more information on this mode[2]

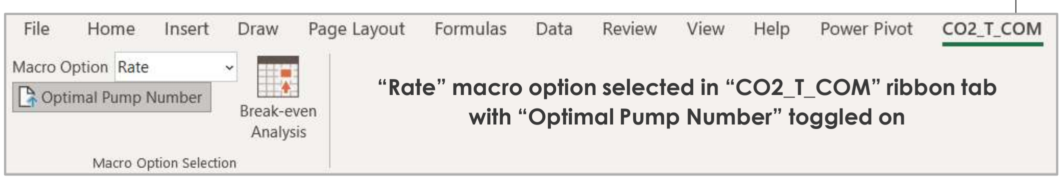
	Q	R	S	T	U	V	W
7	C. First-Year Break-Even Price of CO2 as a Function of Length of Pipeline						
8	Enter a blank cell in column Q to indicate the end of input values						
9 / 10 / 11	Length of pipeline miles	First Year Price base year 2011$/tonne	First Year Price first yr of proj 2018$/tonne	First Year Price first yr of transp 2021$/tonne	User-Defined Number of Pumps	Minimum Inner Pipe Diameter in	Selected Nominal Pipe Diameter in
12	62.0	1.90	2.21	2.37	1	11.51	12.00
13	100.0	3.80	4.43	4.74	1	12.63	16.00
14	150.0	5.54	6.45	6.91	1	13.66	16.00
15	200.0	7.27	8.47	9.07	1	14.45	16.00
16	250.0	9.01	10.49	11.23	1	15.09	16.00
17	300.0	13.86	16.14	17.28	1	15.63	20.00
18	350.0	16.12	18.77	20.10	1	16.10	20.00
19	400.0	18.37	21.39	22.90	1	16.53	20.00
20	450.0	20.63	24.02	25.72	1	16.91	20.00
21	500.0	22.88	26.64	28.52	1	17.26	20.00
22	600.0	27.39	31.90	34.15	1	17.89	20.00
23	700.0	31.90	37.15	39.77	1	18.43	20.00
24	800.0	36.41	42.40	45.39	1	18.92	20.00
25	900.0	52.67	61.34	65.67	1	19.36	24.00
26	1,000.0	58.49	68.11	72.92	1	19.76	24.00
27	1,250.0	73.02	85.04	91.04	1	20.64	24.00
28	1,500.0	87.56	101.97	109.17	1	21.39	24.00
29	1,750.0	102.10	118.90	127.29	1	22.04	24.00
30	2,000.0	116.64	135.83	145.42	1	22.63	24.00

Example inputs and results for Table 1C on “Main” sheet with “Optimal Pump Number” toggled off

How CO2_T_COM Works

Using Macro to Calculate Results for Multiple Values of Input Variables (Table 1D in "Main" sheet provides results for different average annual CO_2 mass flow rates)

- User specifies inputs from Slide 16 and others from slides 8, 9, 12, and 13
  - User enters number of booster pumps if fixed number of booster pumps is desired for all outputs in Table 1D
- User enters up to 45 different average annual CO_2 mass flow rates for evaluation in Column Y in Table 1D on "Main" sheet
- In "CO2_T_COM" ribbon tab
  - Toggle "Optimal Pump Number" on (optimal number of pumps) or off (user input)
  - Select "Rate" in "Macro Option" drop-down menu
  - Press "Break-even Analysis" button to run "Goal_Seek_Price" macro
- After macro is complete
  - Text box appears with message: "Execution Complete for "Goal_Seek_Price Macro! Run time of X minutes"



"Rate" macro option selected in "CO2_T_COM" ribbon tab with "Optimal Pump Number" toggled on

- After macro is complete (cont'd)
  - Macro returns first-year break-even CO_2 price, number of pumps, minimum inner pipe diameter, and nominal pipe diameter for each average annual CO_2 mass flow rate in Column Y
- See Section 1.2.4 in model's user's manual for more information on this mode[2]

	Y	Z	AA	AB	AC	AD	AE
7	**D. First Year Break-Even Price of CO2 as a Function of the Transport Rate**						
8	Enter a blank cell in column Y to indicate the end of input values						
9	**Annual Average**	**First Year Price**	**First Year Price**	**First Year Price**	**Optimal**	**Minimum Inner**	**Selected Nominal**
10	**CO2 Mass Flow**	base year	first yr of proj	first yr of transp	**Number of**	**Pipe Diameter**	**Pipe Diameter**
11	**Rate in Mt/yr**	**2011$/tonne**	**2018$/tonne**	**2021$/tonne**	**Pumps**	**in**	**in**
12	1.00	5.60	6.52	6.98	0	7.52	8.00
13	2.00	3.14	3.66	3.92	0	9.81	10.00
14	3.00	2.35	2.74	2.93	0	11.47	12.00
15	4.00	2.02	2.35	2.52	1	11.20	12.00
16	4.55	1.81	2.11	2.26	1	11.77	12.00
17	5.00	1.92	2.24	2.40	0	13.95	16.00
18	7.50	1.54	1.79	1.92	1	14.26	16.00
19	10.00	1.24	1.44	1.54	0	18.21	20.00
20	12.50	1.25	1.46	1.56	1	17.36	20.00
21	15.00	1.06	1.23	1.32	0	21.29	24.00
22	17.50	0.91	1.06	1.13	0	22.59	24.00
23	20.00	1.05	1.22	1.31	0	23.78	30.00
24	22.50	0.94	1.09	1.17	0	24.89	30.00
25	25.00	0.84	0.98	1.05	0	25.92	30.00
26	27.50	0.77	0.90	0.96	0	26.89	30.00
27	30.00	0.70	0.82	0.88	0	27.81	30.00
28	40.00	0.68	0.79	0.85	0	31.07	36.00
29	50.00	0.55	0.64	0.69	0	33.86	36.00
30	75.00	0.46	0.54	0.58	0	39.59	42.00
31	100.00	0.43	0.50	0.54	0	44.24	48.00
32	150.00	0.54	0.63	0.67	1	45.24	48.00
33	200.00	0.99	1.15	1.23	3	44.21	48.00
34	300.00	1.94	2.26	2.42	7	45.21	48.00
35	500.00	5.48	6.38	6.83	21	45.29	48.00

Example inputs and results for Table 1D on "Main" sheet with "Optimal Pump Number" toggled on

How CO2_T_COM Works

Using Macro to Calculate Results for Multiple Values of Input Variables (Table 1E in "Combo Results" sheet provides results for different annual average CO_2 mass flow rates, pipeline lengths, and elevation changes along pipeline)

- User specifies inputs from Slide 16 and others from slides 8, 9, 12, and 13
  - User enters number of booster pumps if fixed number of booster pumps is desired for all outputs in Table 1E
- User enters different average annual CO_2 mass flow rates (Column A), pipeline lengths (Column B), and elevation changes (Column C) in Table 1E on "Combo Results" sheet
  - Make cell in row after last row with input data blank in Column A to indicate no more input data for macro
- In "CO2_T_COM" ribbon tab
  - Toggle "Optimal Pump Number" on (optimal number of pumps) or off (user input)
  - Select "Combo" in "Macro Option" drop-down menu
  - Press "Break-even Analysis" button to run "Goal_Seek_Price" macro

"Combo" macro option selected in "CO2_T_COM" ribbon tab with "Optimal Pump Number" toggled off

- After macro is complete
  - Text box appears with message: "Execution Complete for "Goal_Seek_Price Macro! Run time of X minutes"
  - Returns first-year break-even CO_2 price, number of pumps, minimum inner pipe diameter, and nominal pipe diameter for each average annual CO_2 mass flow rate, pipeline length, and elevation change in Table 1E
- See Section 1.2.4 in model's user's manual for more information on this mode[2]

This sheet provides multi-scenario capability and has a table where the user can provide a number of key inputs (orange cells) and see key results

Clear Table 1E Contents

E. First Year Break-Even Price of CO2 Based on Three Input Variables — Enter a blank cell in column A to indicate the end of inputs

Annual Average CO2 Mass Flow	Pipeline Length	Elevation Change	First Year Price base year	First Year Price first yr of proj	First Year Price first yr of transp	User-Defined Number of Pumps	Minimum Inner Pipe Diameter	Selected Nominal Pipe Diameter	Note
Mt/yr	mi	ft	2011$/tonne	2018$/tonne	2021$/tonne	Pumps	in	in	
4.30	50.00	0.00	1.59	1.85	1.98	1	11.05	12	
4.30	100.00	0.00	3.80	4.43	4.74	1	12.63	16	
4.30	200.00	0.00	7.27	8.47	9.07	1	14.45	16	
4.30	300.00	0.00	13.86	16.14	17.28	1	15.63	20	
4.30	500.00	0.00	22.88	26.64	28.52	1	17.26	20	

Example inputs and results for Table 1E on "Combo Results" sheet with "Optimal Pump Number" toggled off

Example Model Results 1

- Results were produced using default values presented in model (including having "Optimal Pump Number" in "CO2_T_COM" ribbon tab toggled on), incorporating pipeline length values in table below within Table 1C on "Main" sheet, and selecting "Length" macro option in "CO2_T_COM" ribbon tab
- Price per mile found by dividing break-even cost by pipeline length

Length of Pipe mi	Optimal Number of Pumps	Pipe Diameter in	Break-Even Cost of CO_2 2018$/tonne	Price per Mile 2018$/tonne-mi
62	1	12	2.21	0.036
100	2	12	3.63	0.036
250	6	12	9.25	0.037
500	13	12	18.70	0.037
750	19	12	27.86	0.037
1,000	26	12	37.31	0.037

Example Model Results 2

- Results were produced using default values presented in model (including having "Optimal Pump Number" in "CO2_T_COM" ribbon tab toggled on), incorporating pipeline length values in table below, annual CO_2 transported (on average) of 30 Mtonnes, and elevation change of 0 ft within Table 1E on "Combo Results" sheet, and selecting "Combo" macro option in "CO2_T_COM" ribbon tab
- Price per mile found by dividing break-even cost by pipeline length

Length of Pipe mi	Optimal Number of Pumps	Pipe Diameter in	Break-Even Cost of CO_2 2018$/tonne	Price per Mile 2018$/tonne-mi
62	0	30	0.82	0.013
100	1	30	1.61	0.016
250	3	30	4.15	0.017
500	7	30	8.58	0.017
750	10	30	12.72	0.017
1,000	14	30	17.14	0.017

Acronyms and Abbreviations

%	Percent
°F	Degree(s) Fahrenheit
CAPEX	Capital costs or expenses
CO_2	Carbon dioxide
DB150	150% declining balance
EIA	Energy Information Administration
FECM	Fossil Energy and Carbon Management
ft	Foot, feet
hr	hour(s)
kW	Kilowatt(s)
mi	Mile(s)
Mtonnes	Megatonne(s) (million tonne[s]
MW	Megawatt(s)
NETL	National Energy Technology Laboratory
NPV	Net present value
O&M	Operation and maintenance
OPEX	O&M costs or expenses
psig	Pound(s) per square inch gauge
QGESS	Quality Guidelines for Energy System Studies
SL	Straight line
tonne	Metric tons (1,000 kilograms)
VBA	Visual Basic For Applications
WACC	Weighted average cost of ` capital
yr	Year(s)

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CONTACT:
David Morgan
David.Morgan@netl.doe.gov